Solar UV exposures measured simultaneously to all arbitrarily oriented leaves on a plant

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Abstract

The possible ramifications of climate change include the influence it has upon the amount of cloud cover in the atmosphere. Clouds cause significant variation in the solar UV radiation reaching the earth's surface and in turn the amount incident on ecosystems. The consequences of changes in solar UV radiation delivered to ecosystems due to climate change may be significant and should be investigated. Plants are an integral part of the world wide ecological balance, and research has shown they are affected by variations in solar UV radiation. Therefore research into the influence of solar UV radiation on plants is of particular significance. However, this requires a means of obtaining detailed information on the solar UV radiation received by plants. This research describes a newly developed dosimetric technique employed to gather information on solar UV radiation incident to the leaves of plants in combination with the measurement of spectral irradiances in order to provide an accurate method of collecting detailed information on the solar UV radiation affecting the canopy and lower leaf layers of individual plants. Variations in the measurements take into account the inclination and orientation of each leaf investigated, as well as the influence of shading by other leaves in the plant canopy.

Keywords: UV radiation; plants; dosimetry; clouds; climate change.

Authors' Accepted Version of:

Parisi, Alfio and Schouten, Peter and Downs, Nathan and Turner, Joanna (2010) *Solar UV exposures measured simultaneously to all arbitrarily oriented leaves on a plant.* Journal of Photochemistry and Photobiology B: Biology, 99 (2). pp. 87-92. ISSN 1011-1344

1. Introduction

Climate change, one of the earth's most important current and future concerns, has a direct influence on the amount of cloud cover in the atmosphere. Variation in cloud cover will impact on the solar ultraviolet (UV – 280 to 400 nm) radiation incident upon ecosystems. Studies have shown that transmission of biologically effective UV radiation to the earth's surface depends on cloud cover, with increased cloud cover decreasing the biologically effective UV radiation transmission through the atmosphere [1,2]. Conversely, depletion of the ozone layer by 1% corresponds to an increase in biologically effective UV radiation by an average of 2% [3] depending on the biological effect of interest. Gies [4] suggested that as the largest moderator of ambient UV radiation, clouds may induce more of an effect on ambient UV radiation than decreasing ozone levels. Overall, the consequences on different ecosystems in relation to changes in solar irradiance due to varying climatic factors may be significant and needs to be investigated. In order to determine these associated consequences resulting from changes in solar UV radiation levels, the current research aims to investigate a new method for quantifying solar UV radiation to plant leaves.

As symbiotic members of the delicate world wide ecosystem, humans and animals rely on plants for survival. Humans cultivate and consume various varieties of plants in large quantities for the purposes of sustenance, energy, fuel, food for animals and of course, plants remove carbon dioxide from the atmosphere and produce oxygen for humans and animals to breathe. Therefore any effects from global changes in climate will require monitoring the UV on plants and hence, more specifically this requires a means of obtaining information on the amount of solar UV radiation to plants.

Recommendations have been made for monitoring UV radiation in the field on crop plants due to changing climates, where the influence of UV to whole plant processes and not just the canopy will be needed for understanding UV effects due to changing the global environment [5]. This requires a means of monitoring UV radiation among the leaf layers of the plant and not just the upper canopy or ground level UV radiation, in order to understand biological effects to plants due to UV radiation. Generally, research projects in greenhouses, growth chambers and in the field that investigate the influence of solar UV on plants, have measured the solar UV incident to a horizontal plane with spectroradiometers and radiometers [6]. However, the UV to the receiving plane of the plant leaves is significantly different to that on a horizontal plane [7]. The variation in the spectral solar UV to vertical surfaces has been reported [8]. The UV to arbitrarily oriented sites on a human form has been measured with a radiometer scanning to different planes [9]. More recently, the solar UV spectra to the vertical sides of the rows of a vineyard have been measured with a portable spectroradiometer [10].

In order to measure the solar UV radiation to plant leaves, the use of dosimeters has been investigated. Dosimeters have been employed to measure the UV exposures (from 280 nm to 320 nm) to a plant canopy in both greenhouse and field studies [7,11]. The dosimeters employed in these studies were based on the polymer polysulphone [12] and were each approximately 3 cm x 3 cm in size. This is acceptable for larger plants, however for smaller sized plants and plants with small leaves, the weight of the dosimeter can change the inclination and the orientation of the leaf resulting in an artificially modified incident UV exposure. Furthermore, for measurements of UV exposures over extended periods, the optical response of the polysulphone dosimeters begins to decrease significantly. The length of time before the dosimeters start to saturate depends on the incident UV irradiance intensity at the surface of the dosimeter film. As a general guide, polysulphone dosimeters start to saturate after an exposure of one day at a sub-tropical site in summer. This necessitates the replacement of the dosimeters on a daily basis for long-term measurements.

To overcome the problem of the size of the dosimeter affecting exposure measurements on small leafed plants, this paper describes the new technique of using miniaturised polysulphone dosimeters to measure the UVB exposures to plant leaves. For the cases of larger plants where exposure measurements are required for periods longer than the dynamic range of polysulphone, this paper presents the new application of the use of the polymer polyphenylene oxide (PPO) [13-16] to quantify the UVB exposures to plant leaves over extended periods.

2. Methods

The plants used in this research were cotton palms (also known as Mexican fan palm: *washingtonia robusta*) located at Toowoomba (27.5^{o} S, 151.9^{o} E, 693 m altitude), Australia. Three cotton palms were utilised, one which was approximately 0.4 m high and clear from other vegetation by at least 2 m distance, the other two approximately 1.5 m to 2 m high and located within a few metres of each other and several kilometres from the smaller cotton palm. The cotton palms were not shaded by other plants during the major part of the solar day, and did not shade each other. Only approximately half of the leaves on each palm were shaded, but the leaves that were shaded changed throughout the day depending on solar zenith angle (SZA) and solar azimuth. Ground surfaces of bare dirt and grass surrounding the cotton palms have low UV albedo values, which indicate they were unlikely to significantly affect the exposure or spectral measurements made around the plants.

2.1 *Spectral UV Irradiances to Plant leaves*

In order to investigate any differences in the spectral UV to the plant leaves, spectral UV irradiances over a waveband running from 280 to 400 nm incident to the planes of the arbitrarily oriented plant leaves were measured by placing the sensor of a spectrometer on a plane parallel to each of the leaves. The spectra were collected using the leaves of the two larger cotton palms. The instrument employed was a USB4000 Plug-and-Play Miniature fibre optic spectrometer (Ocean Optics, Inc., USA) measuring in integrated 0.2 nm steps through the wavelength range. To enhance accuracy, the spectrometer was calibrated to a double monochromator UV spectroradiometer (Bentham model DTM300, Bentham Instruments, Reading, UK) from 280 nm to 400 nm. The spectroradiometer was calibrated with a 150 W quartz tungsten halogen lamp with calibration traceable to the National Physical Laboratory, UK standard. Once calibrated, the USB4000 has an average of ±10% uncertainty for the integrated UVB waveband (300 nm to 320 nm) compared to the Bentham spectroradiometer. The two larger palms were used in this investigation as they were more accessible for the spectral measurements with the USB4000 spectrometer in comparison to the smaller palm. For measuring the spectral UV incident to the smaller palm it would have been necessary to damage or bend the leaves to situate the diffuser at a suitable position for the measurements, which would defeat the purpose of this study. The spectral UV irradiance was measured on the morning of October 14, 2008 over a SZA range of 37.1° to 24.7° and at midday and afternoon on October 20, 2008 over a SZA range of 18° to 22.7° and 52.5° to 60.6°. Total sky cloud cover ranged from 0% to 30% as imaged by a Total Sky Imager (TSI) (Yankee Environmental Systems, Inc. Model 440A). Downwelling irradiances were recorded when the sun was not obscured by cloud.

2.2 *UVB Exposures to Plant Leaves*

Previous research has measured the UVB to the canopy of a small plant by deploying polysulphone dosimeters that were 3 cm x 3 cm in size, on thin metal rods to allow measurement of the UVB over a plant canopy [11]. Polysulphone has a similar UVB sensitivity to a variety of action spectra associated with plant growth or effects and can provide as much information as other broadband sensors when the exposures are weighted according to the appropriate action spectrum. [17]. However, measurement of the UVB exposures to the plant leaves requires the deployment of the dosimeters to the surface of the plant leaf. For a small plant, this will alter the leaf inclination. This can be overcome by the use of polysulphone dosimeters that have been miniaturised with lightweight cardboard frames measuring approximately 15 mm × 10 mm each with a circular aperture of 6 mm. These have been previously tested for measuring erythemal UV to humans [18]. The average weight of these dosimeters is 0.03 g compared to the weight of 0.7 g for each conventionally sized dosimeter [18,19]. A comparison of the miniaturised dosimeter with respect to a dosimeter of the type that has been previously employed is provided in Figure 1. The polysulphone film dosimeters used in this investigation were cast at a thickness of approximately 40 μm.

In order to deploy the dosimeters for measuring the UVB exposures incident on the small leaves of plants, the miniaturised dosimeters were attached with tape to the upper side and the under side of each of the leaves of a small cotton palm. The cotton palm was approximately 0.4 m high with four leaves and is shown in Figure 2 with the dosimeters attached. For a comparison with the UVB to a horizontal plane, two dosimeters situated parallel to the horizontal were deployed over the same exposure measurement period. This exposure measurement period was for an SZA of 46° to 88° on 13 May between 8.00 and 17.00 EST. Pre- and post-deployment absorbance was measured for each miniaturised dosimeter at 330 nm using a spectrophotometer (model UV1601, Shimadzu Co., Kyoto, Japan). Total sky cloud cover for this period recorded by the TSI ranged from 0% to 15%.

The difference between the pre- and post-deployment exposure of the miniaturised dosimeters was calibrated by exposing a series of dosimeters on a horizontal plane to solar UV for a period of one day while concurrently measuring the solar UVB with a spectroradiometer (Bentham model DTM300, Bentham Instruments, Reading, UK) having specifications as described by Parisi and Downs [20]. Calibrations were carried out on a regular basis, and for this study were carried out within the same season and in similar atmospheric conditions, to limit polysulphone variability [21, 22].

2.3 *UVB Exposures to Plant Leaves over Extended Periods*

Dosimeters with a dynamic range of approximately five days were developed and employed for the measurement of the UVB exposures to each plant leaf over extended periods. These dosimeters were based on polyphenylene oxide (PPO) [13,14] that has been previously used to measure UV exposures in air and to measure UVB exposures in aquatic environments [15,16]. PPO, like polysulphone, can be weighted against plant damage action spectra, as there is similar response sensitivity within the UVB waveband. PPO has been shown to have a response in the UVB that is temperature and dose rate independent [14]. The PPO dosimeters were fabricated at a thickness of approximately 40 µm. Separate pieces of PPO film were attached with tape to a holder with an overall size of 3 cm x 3 cm. Each holder has a central aperture of 1.2 cm x 1.6 cm over which the film is placed.

The amount of UVB photodegradation occurring to the PPO dosimeters was quantified by measuring the change in optical absorbance at 320 nm in a spectrophotometer (model UV1601, Shimadzu Co., Kyoto, Japan). 320 nm was utilised as the largest change in optical absorbance occurs at this wavelength for PPO film [15,16]. The PPO dosimeters were calibrated in spring by exposing a series of dosimeters on a horizontal plane to solar UV for a period of seven days while concurrently measuring the solar UVB with the spectroradiometer.

The exposures to each of the leaves of two similarly sized plants (the same used in Section 2.1, using the same leaf number allocations) were measured with the PPO dosimeters between 11.05 am on 15

September 2008 and 10.30 am on 23 September 2008. Over this period, the minimum SZA was 27.7°. During the period of exposure, the total sky cloud cover ranged from 0% to 100%, with some days recording no cloud cover while other days had a minimum of 50% cloud cover.

3. Results and Discussion

3.1 *Spectral UV Irradiances to Plant leaves*

The spectral UV irradiances to the plane of two leaves on the cotton palm are shown in Figure 3 (a). The leaves numbered 5 and 9 have an inclination of 30° and 70° respectively and an azimuth of 80° and 220° respectively. All the leaf inclination and azimuth values for the two larger cotton palms are listed in Table 1. In this research the downwelling spectral irradiance is incident to the top side of each leaf and the upwelling spectral irradiance is incident to the bottom side of each leaf. The measured irradiances shown in Figure 3 (a) were weighted with the Flint and Caldwell plant growth inhibition action spectrum [23] to provide the biologically effective spectral UV (UV_{BE}) as shown in Figure 3 (b). The weighting of the spectral irradiance with this particular action spectrum shows that plant growth inhibition is generally higher in the UVB radiation waveband than the UVA waveband while the differences between the top side irradiances and the bottom side irradiances are more pronounced in the UVA compared to UVB. This is mainly due to the higher proportion of diffuse UV at the shorter wavelengths. This difference is also seen in Figure 3 (c). The differences are also dependent on the inclination and azimuth of the leaf and the SZA. The inclination and azimuth of the leaves, clearly affects the biologically effective exposure reaching both sides of the leaf of the plant. Figure 3 (c) shows that the underside of a leaf not on a plane perpendicular to direct UV incident irradiance receives much lower proportions of UVA wavelengths compared to that of a plane that is perpendicular to direct incident UV irradiance, for example leaf 6 where the leaf is facing to the north. The ratios in this figure were calculated by integrating the spectral UV measurements over the UVA and UVB wavebands for both the upwelling and downwelling radiation around each leaf, and comparing to the integrated spectral measurements per waveband made on a horizontal plane.

As this data was collected on a clear day, all downwelling spectral irradiances have a large proportion of direct UV of the total irradiance in comparison to upwelling irradiances. As the number of cloudy days increases in a given year, the difference between upwelling and downwelling irradiance intensity begins to decrease. Some studies have indicated that UV transmittance through clouds is wavelength dependent for certain conditions [24]. Therefore, if clouds do have a significant wavelength dependent influence, changing climatic conditions with increased cloud may change the proportions of UVB and UVA in the atmosphere. A previous study has suggested that while clouds produced short term changes in UV radiation reaching the earth, there was no change in UV radiation due to wavelength dependency in the long term [25]. However, given the potential effects of climate change and a number of studies that do suggest UV wavelength dependency due to clouds as reviewed in Calbó et al. [26], any possibility of changing the proportions of UVB to UVA in the atmosphere by clouds would suggest the need to investigate this phenomenon further. Despite constituting just a small portion of the electromagnetic spectrum, UVB is significantly important to biological effects in plants and animals [27]. Krizek [28] reviewed the interactive effects of UVB, UVA and photosynthetically active radiation (PAR – 400 to 700 nm) and showed that the overall balance of irradiance in different wavebands has an effect on the plant sensitivity to changes in UVB irradiance. Different biological effects will mean different proportions of irradiance waveband interaction. Any future changes to spectral UV irradiances will require close monitoring of changes in the proportions of direct and diffuse UVB and UVA radiation, as it has been suggested that future changes in climate will require knowledge of spectral differences as well as broadband UVB [5].

Spectral irradiance measurements such as those described in this research will be useful in determining proportional changes between UV radiation and PAR. Any increased cloud cover will increase the diffuse proportion of UV radiation more than the diffuse proportion of PAR in comparison to the decrease of direct UV or PAR. Calbó et al. [26] reported that the cloud effect on UV radiation is 15 to 45% less than the effect on total solar radiation, thereby indicating that proportions of UV to PAR radiation would be changing with variation in cloud cover. Also, changes in the total proportions of UV to PAR can significantly impact on plant features such as total biomass and plant height [28]. The instrument used to collect this spectral data would also be suitable for measurements of both UV and PAR as it records spectral measurements from 280 nm to 800 nm. The drawback to using a spectrometer is the lack of multiple sensors to record simultaneous spectral irradiances. Dosimetry and the miniaturised form of dosimetry allow simultaneous measurement at multiple sites by measuring the UV exposure at the different layers of the plant canopy. Thus, the proposed methodology detailed in this investigation combines spectral measurement of the UV and PAR wavebands where possible with detailed spatial measurements of the UV taken at different orientations in a plant canopy by application of lightweight and extended range dosimetry to provide a better understanding of the solar radiation influencing the growth of specific plant species. The need for leaf layer analysis is shown in Figure 3 (c), in which the ratio of UV exposure on the leaf to the UV exposure on a horizontal surface indicates the overall variation of UV irradiance on different leaf layers. A dense smaller leafed plant would show more variation among the leaf layers than the palm used in this study.

3.2 *UVB Exposures to Leaves on a Small Plant*

Figure 4 shows the UVB exposures to the leaves of the small plant. Dosimeter locations 1 to 4 are the exposures to the upper sides of the leaves, locations 5 to 8 are the exposures to the under sides of the leaves and dosimeter location 9 is the exposure to a horizontal plane. The exposures to the upper sides of the leaves range from 4.4 to 23.8 kJ m^{-2} and the exposures to the under sides range from 0.07 to 6.1 kJ m^{-2}. The average of the percentage exposure for each dosimeter location relative to the UVB exposure on a horizontal plane over the same period is 47% (range 14% - 78%) for the upper sides and 6.6% (range 0.2% - 20%) for the under side. The value of 20% was for a leaf inclined at approximately 85° to the horizontal. Consequently, the leaf was exposed to a larger sky view compared to the leaves with the small inclination, allowing interception of a higher amount of solar radiation to the undersides of leaves. These leaves with the smaller inclinations had percentage exposures of 5% or less. Compared to the dosimeter exposed on the horizontal plane, location 1 shows that the upper side of the leaf must also approximate a horizontal plane, as the UVB exposure values were very similar. The lower side of the dosimeter (location 5) confirms this, with the lowest UVB exposure of all the dosimeters, indicating that only diffuse UVB was incident to this location. Higher recorded UVB exposures for the upper side of the leaf compared to the horizontal would suggest the leaf is inclined with the upper side facing the sun. Of course, this represents effectively only those leaves at the top of a canopy and does not apply to lower layer leaves where there is shading by the leaves higher in the canopy.

3.3 *UVB Exposures to Plant Leaves over Extended Periods*

The UVB exposures to the upper and lower sides of the plant leaves for the larger plant over an extended period are provided in Figure 5. The UVB exposures incident on the upper sides of the leaves are the shaded columns and the UVB incident on the lower sides of the leaves are the unshaded columns. For plant 1, the average exposure to the lower sides of the leaves is 17.9% of the average exposure to the upper sides of the leaves. For plant 2, this percentage is 39.2%. The average of the upper sides’ exposures for plant 1 is 85% of the same average for plant 2 and the average of the lower sides’ exposures for plant 1 is 60.6% of the same average for plant 2. These ratios of the exposures are not unity due to the inherent differences in the structure and positioning of the plants and the inclination and orientation of each leaf.

The average percentage exposure compared to a horizontal plane for the upper side of the leaves is 96% (range 31.3% - 128%) and the average percentage exposure compared to a horizontal plane for the under side of the leaves is 20.2% (range 6.0% - 70.9%). Exposures above 100% indicate that the leaf or leaves were orientated in a position where they received a greater amount of UV exposure in comparison to the ambient UV on a horizontal plane. This is an orientation where the leaf is normal to the position of the sun for most of the day. The UV exposures to dosimeter locations 6 and 22 illustrate the influence of the leaf azimuth on the UVB exposure. These particular leaves had inclinations of 40° and 80° above the horizontal plane respectively with azimuths of 180° and 270°. The leaf at location 6 has a higher exposure as the leaf is facing towards the north and is inclined at a lower angle than leaf 22. At the Southern Hemisphere location of this research, this leaf was in sun throughout the entire day. In comparison, the leaf at location 22 is facing towards the west and as a result the upper side of this leaf would have only received maximum exposure in the afternoon, as the leaf is inclined at 80°.

3.4 *Combining all Techniques*

For each of the leaves on both the small and large plants, the UVB exposures varied due to the inclination and azimuth of each leaf as well as the variable shading of individual leaves by other leaves through the daily exposure cycle. Therefore, if every leaf on a plant is exposed to varying UVB exposures compared to UVB exposure on a horizontal surface, studies that require knowledge of UVB exposure to determine biological effects will require knowledge of the variability of the UVB exposures, including irradiances to upper and lower sides of leaves. Apart from inclination, azimuth and shading, UV exposures to the lower sides of leaves may be influenced by other external factors such as albedo of the surrounding environment and cloud.

For smaller plants, the surrounding ground cover is likely to be grass, bare earth or some form of decomposing plant or animal matter. Albedo is wavelength dependent but, for these types of surfaces the spectral albedo does not generally exceed three percent for vegetation and eight percent for earth (depending on water content) [29]. In instances where plants are located near buildings, there is a possibility that UV reflection from metal surfaces could increase UVB exposures [30, 31]. Overall, the exposures to the underside of leaves are mostly dependent on diffuse UV, of which UVB constitutes a higher percentage due to the higher relative amount of Rayleigh scattering at these shorter wavelengths. Overall, the inclination and azimuth of each leaf will affect the exposures to the underside of the leaf more by changing the proportion of direct to diffuse UV available at the inclination and azimuth.

Cloud will affect the total exposure and the shape of the spectral irradiance measured at the different layers of the plant. When intermittent cloud is present, the continual changes in UV irradiance can be difficult to measure with a spectrometer alone. Dosimetry provides the continual measurement of UV exposure and can take into account the fluctuation of UV exposure over time. The measurement of cloud affected spectral data is complicated by cloud types, cloud position with respect to the sun and total sky view. Future research using the techniques presented in this paper could be used to measure the influence of cloud to the canopy of plants. This preliminary research has demonstrated that UV exposures are influenced by the orientation of leaves in the canopy in mostly clear sky conditions and is a fundamental physical parameter that must be taken into account in any future research which may ascribe changes in UV exposure caused by changes in cloud cover.

Future work with dosimetry may be improved further. Filters could be used to further develop more accurate spatial distributions of plant canopy exposure in desired wavebands. Recent work with dosimeters has been carried out using a combination of polysulphone and a secondary material cast in film form, such as nalidixic acid [32]. This dosimeter has displayed a spectral response that extends into the UVA spectrum, and can be used to approximate the plant growth inhibition action spectrum [23]. Using the new combination polymer dosimeter in a miniaturised form in future work may allow better approximation of the biological effect of plant growth inhibition UV exposures over short periods throughout leaf layers on a plant. Other future work would benefit from PAR measurements made in combination with the techniques used in this study.

4. Conclusion

Measurement of the spectral irradiance using a spectrometer and integrated irradiance by means of applied dosimetry to different leaf layers and structures has shown the UVB intercepted by the leaves is influenced by the inclination, azimuth and shading of each leaf. Possible changes in the relative proportions of UVB to UVA or PAR due to clouds may affect the biological effects to plants. The use of dosimetry allows for the continuous monitoring of the UV irradiance variation throughout leaf layers.

Miniaturised dosimeters have been used to measure UVB exposures to the leaves of a plant in the field. The advantage of this technique is that it provides the ability to integrate the exposures over a given period and take into account variations in cloud cover, shading, inclination, orientation and atmospheric conditions such as ozone and aerosols. Additionally, the miniaturised dosimeters allow measurement to small leaves without changing the inclination of the leaves. These dosimeters are suitable for measuring UVB exposures over the period of a day, at which point polysulphone starts to saturate. The use of PPO dosimeters which have a larger dynamic range, has allowed the characterisation of the UVB environment to the leaves of a plant over an extended period of time without the need for daily replacement, which would be required if polysulphone was employed for the same task.

The miniaturised dosimeters, the long term dosimeters and the measurement of spectral irradiances using the portable spectrometer, as described in this paper for use on the leaves of plants has increased the number of ecosystems in which the UVB can be characterised in a non invasive manner. The dosimeters form an important tool in studies involving examination of the UV environment and studies developed to investigate the effects of changes in the UV environment to plants and can easily be supplemented with the use of a portable spectrometer. The implications of which include improving the characterisation of the UV exposures to native plant species within a changing global climate.

5. References

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Table 1. The azimuth (degrees from magnetic north where magnetic north is zero) and inclination (degrees above the horizontal) of each leaf used in spectral irradiance measurements and UV exposure measurements using PPO dosimeters.

Leaf number	Azimuth	Inclination
1	0	20
2	320	30
3	40	35
4	90	25
5	80	30
6	180	40
7	190	35
8	220	50
9	220	70
10	20	75
11	120	50
12	0	10
13	40	30
14	120	45
15	160	25
16	170	35
17	160	50
18	200	30
19	280	25
20	300	40
21	220	90
22	270	80

List of Figures

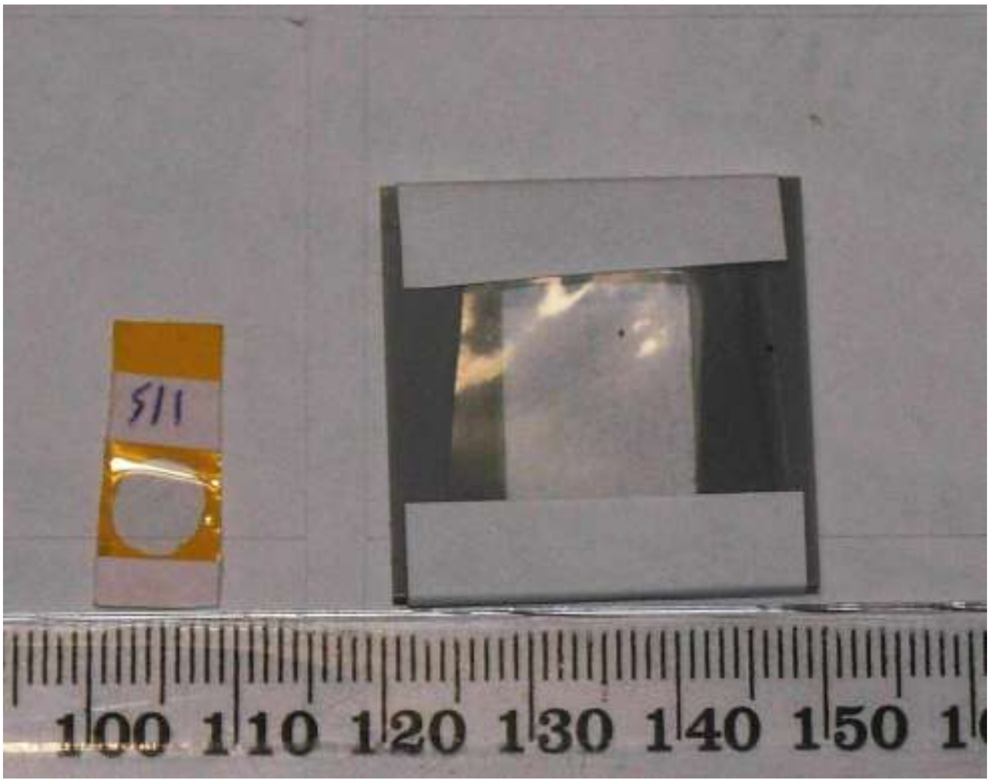
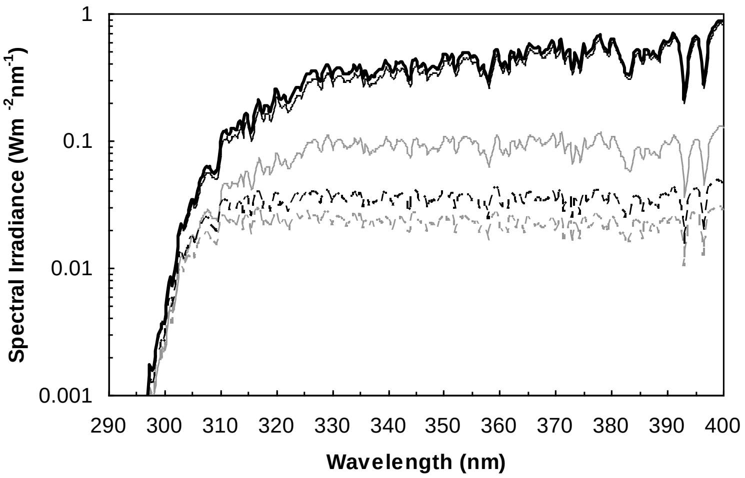


Figure 1 – The miniaturised polysulphone dosimeter for UVB measurements on small plants and the PPO dosimeter for extended UVB measurements on larger plants.

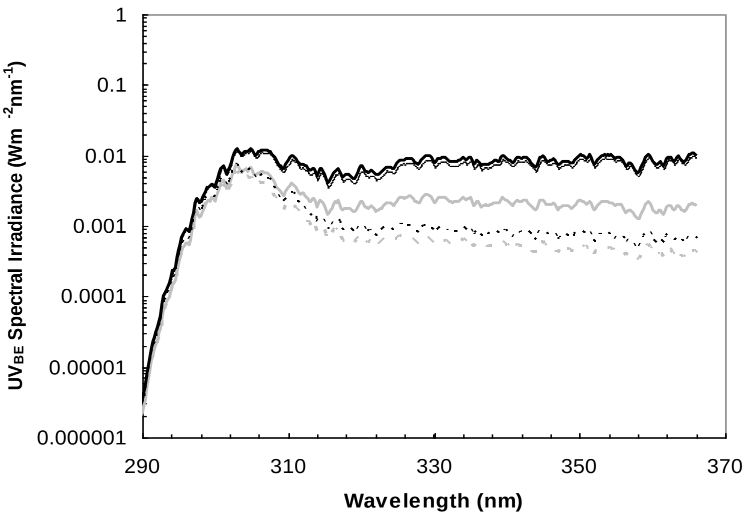
Figure 2 - The miniaturised dosimeters attached to each leaf of a small plant (~0.4 m high) in the field. The dosimeters that are visible are marked with boxes.

(a)



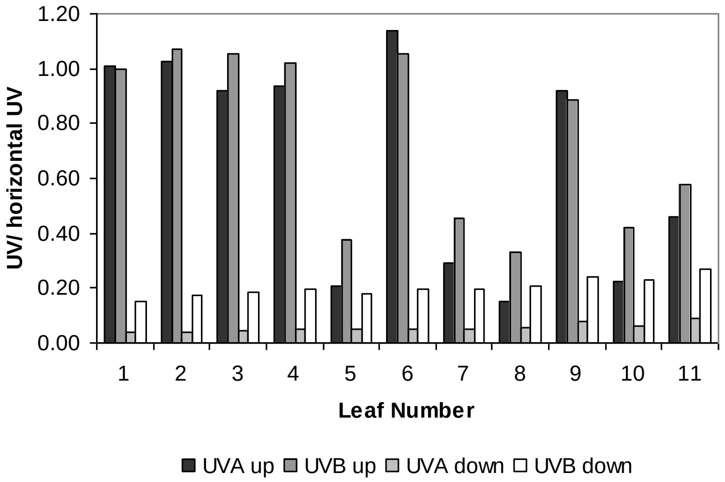
Spectral Irradiance (Wm -2nm-1)
1
0.1
0.01
0.001
290
300
310
320
330
340
350
360
370
380
390
400
Wavelength (nm)

(b)



UVBE Spectral Irradiance (Wm -2nm-1)
1
0.1
0.01
0.001
0.0001
0.00001
0.000001
290
310
330
350
370
Wavelength (nm)

(c)



UV/ horizontal UV
1.20
1.00
0.80
0.60
0.40
0.20
0.00
1
2
3
4
5
6
7
8
9
10
11
Leaf Number
UVA up
UVB up
UVA down
UVB down

Figure 3 – (a) The solar UV spectra incident on the upper sides and the lower sides of two leaves. (b) the biologically effective UV spectral irradiance weighted against the plant growth inhibition action spectrum (Flint and Caldwell, 2003). The thick black line is the UV irradiance on a horizontal surface, the solid lines are the upper side of the leaf and the dashed lines represent the lower side of the leaf. Dark lines are leaf 9 and grey lines are leaf 5. (c) The UV exposures of plant 1 using the integrated spectral irradiances for each waveband for the upper and lower side of each leaf.

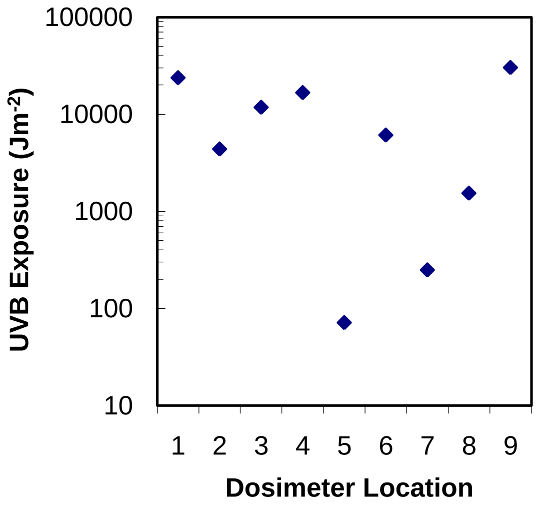


Figure 4 – The UVB exposures measured to each leaf of the small plant with the miniaturised dosimeters. Dosimeter locations 1 to 4 are the exposures to the upper sides of the leaves, locations 5 to 8 are the exposures to the under sides of the leaves and dosimeter location 9 is the exposure to a horizontal plane.

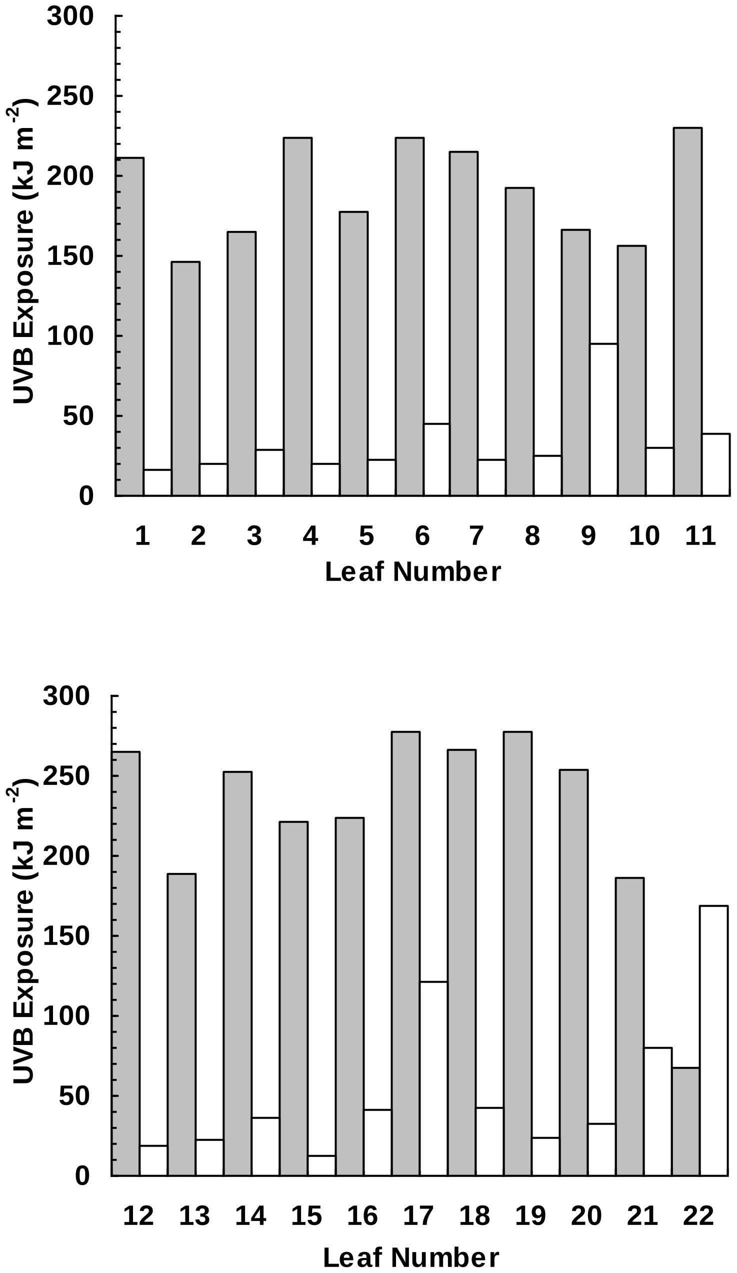


Figure 5 – The UVB exposures over an extended period of five days to the upper sides (shaded columns) and the under sides (unshaded columns) of the leaves of plant 1 (upper graph) and plant 2 (lower graph).